

# Cost Optimisation of an Instrument Suite at an Accelerator-Driven Spallation Source

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This article presents an optimisation of performance and cost of neutron scattering instrumentation at the European Spallation Source. This is done by trading detailed cost functions against beam transmission functions in a multi-dimensional, yet simple, parameter space. On the one hand, the neutron guide cost increases as a power of the desired beam divergence, and inversely with the minimum wavelength, due to the supermirror coating needed. On the other hand, the more neutrons are transported to the instrument the greater are the shielding costs to deal with the gamma rays that result from the eventual absorption of the neutrons. There are additional factors in that many of the parameters defining the neutron guide geometry are continuous variables, and the straightness of the guide increases the transmission of high energy spallation products, which affect the specifications of particularly heavy hardware, such as heavy shutters and additional shielding, beam stops etc. Over the suite of 16 instruments, a maximum potential cost saving is identified in the vicinity of 20 M€, with negligible penalties on instrument performance and bandwidth, by trading minimum neutron wavelength  $\lambda$  against total optical costs and shielding costs. Finally, these cost calculations are shown to be consistent with those at real world, existing spallation source facilities.

## I. INTRODUCTION

Modern neutron scattering instruments at spallation sources are expensive, costing in the region of 12-20 M€. Typically, an instrument has a working lifetime of approximately 10-20 years. At the time of writing, the budget for the instrument suite of 16 instruments at the ESS, including ramping up all of the support functions, is around 211 M€, from a total facility budget of 1 843 M€.

It is imperative that facilities of this scale strike the appropriate balance of cost and performance, to maximise the return on investment and create as large a benefit as possible from the available resources.

It will be shown later in this report that a significant fraction of the cost of each instrument, around 30-50%, is spent on shielding and neutron optical components [1]. Indeed, shielding is the main cost driver, costing around 30% of the total budget. Shielding is directly linked with instrument background noise — and hence instrument user quality — along with safety and regulatory factors. As such, one might expect that this area of expertise would receive more attention in the neutron scattering community than it does.

In the past, shielding and optics tended to be optimised somewhat independently. We show in this article that successful cost optimisation and instrument background reduction is considerably easier if the whole system is designed and optimised together as a single task for an expert team. Indeed, at the European Spallation Source (ESS), Sweden, and the Paul Scherrer Institut (PSI), Switzerland, a core risk and cost minimisation strategy is to design the optics and shielding systems to-

gether by co-located personnel using a common set of tools and with thorough cross-checking in place.

In this article, an initial stage of this work is summarised. Preliminary specifications and requirements are identified for the instrument suite beamline systems, and the cost of those systems is minimised to a critical performance metric value to be defined shortly. Systems exceeding this metric value could be defined as being over-engineered, and systems below this value as under-performing. This allows us to define an optimum cost for the instrument suite.

Finally, it will be shown that by strategically selecting a subset of “primary” instruments, which are fully optimised, and reducing the specifications of the remainder into the under-engineered category, a further set of cost savings are possible with a viable suite, with a small decrease in performance.

## II. INPUT DATA AND COST ESTIMATES

There are two beam scenarios to consider in this initial study. The first evaluates the shielding costs for a direct beam with line of sight back to the source, and the latter is with part of the beam line curved out of line of sight.

### A. Line of Sight Option

This shielding is thick, since it must protect against scattered high energy (MeV - GeV) neutrons and gamma rays. We use a rough cost estimate for an enhanced concrete instrument cave for straight beamlines, based on the PSI instrument “BOA”, increased in thickness to 2 metres, and accommodating  $5 \times 5 \times 5 \text{ m}^3$  of instrument space. These specifications were for a generic instrument, based

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partly on calculations of minimum thickness for a MW spallation source with a GeV proton beam, and partly on measurements at PSI and SNS on fast neutron transmission and prompt pulse backgrounds, which usually adversely affects instrument performance.

A completely straight beamline also requires a heavy chopper — commonly known as “T0”, “t-zero”, or “Prompt Pulse Suppression” (PPS) choppers: these are heavy choppers that attenuate the high-energy particles during proton illumination of the spallation target. The cost of these T0 choppers was estimated roughly and somewhat optimistically by the ESS Chopper group, assuming some economy of scale by manufacturing multiple units and minimising development costs.

The instrument also requires a heavy shutter, capable of blocking the high energy beam and allowing access to the sample area. A study performed by the ESS engineering department for an SNS-style cylindrical drum shutter was completed in 2013, which provided the cost estimates for this item. Note that a guillotine-style shutter outside the monolith is not recommended due to the vertical streaming paths this would generate next to the short instruments.

## B. Out of Line of Sight

This option has a similar cost of guide shielding as that of an instrument at a reactor source. A thickness of 60 cm of regular concrete was found via preliminary Monte-Carlo calculations to attenuate the radiation sufficiently to safe levels ( $1.5 \mu\text{Sv/h}$  total simulated dose rate [11]). 60 cm of concrete is slightly thicker than other lower power facilities but not excessive. For example, on TS2 at ISIS, 35 cm of concrete shielding is sufficient, although in that case a heavy shutter can be closed if there is a safety hazard on a beamline.

## C. Concept Neutral Costs

For the instrument cave, we assume an enclosure similar to those at the LET and OFFSPEC instruments on TS2 at ISIS, in the UK. These are hollow steel cans filled with borated paraffin wax.

The cost of concrete comes from ESS Conventional Facilities Department, and is the price for reinforced concrete, cut and shaped and installed.

The cost of raw metals come from the London Metal Exchange.

In all beamlines, it is anticipated to use at least three laminate collimation blocks within the shielding bunker and/or curved sections, to reduce the streaming of fast neutrons into the guide system downstream. These may be conceptually similar to the collimator on the CHIPIR beamline at ISIS, or indeed much smaller, and spread between multiple units. Other names for these devices could include “horse-collars” or “fast neutron scrapers”.

For the purposes of this study, we assume these to be three units of  $1 \text{ m}^3$  of copper with a small channel cut through the centre.

A summary of the items can be constructed as follows:

**ISIS-TS2 Wax Cave** based on LET and OFFSPEC, for thermal beams out of line of sight. Cost: 950 kGBP several years ago, rounded to 1.5 M€.

**PSI Concrete Cave** based on BOA, for beams with direct line of sight: 2 M€.

**Heavy beam shielding** for beam areas within line of sight: approx. 7770 €/m.

**Light beam shielding** for thermal beams out of line of sight: approx. 2600 €/m.

**Laminate collimation blocks** initially costed as 100% copper: 47 k€ per unit, 3 units per beam.

**T0/PPS Chopper** : only necessary for straight beamlines with line of sight of source, 750 k€.

**Heavy shutter** : only necessary for straight beamlines with line of sight of source, 750 k€.

Not included in this budget estimate are the ESS guide bunker and target shielding, which absorb a large fraction of the radiation dose. We only include shielding items outside the common shielding areas. This has a potential cost-saving from the perspective of the instrument project, since — if the geometry loses line of sight within the bunker — the instrument only needs thermal beam shielding in its budget.

The optical system costs are evaluated for the full length of the beamline. However, curving out of line of sight quickly, with a radius of 1.5 km for example, increases the optical cost compared to a gentle curvature of several km, because the neutron supermirrors need to be engineered to reflect at larger grazing angles. At still tighter radii, of a few hundred metres, the neutron guides are normally divided into several thin channels known as “multi-channel benders”. These require more precision manufacturing, with a greater surface that needs to be coated with supermirrors. It should be clear that, whilst curving out of line of sight quickly can reduce the shielding cost, the optical cost is increasing against the shielding cost saving. These two costs are traded against each other in our optimisation.

Optical component cost equations were provided to ESS as part of a market survey, and these are commercial-in-confidence details that cannot be widely shared. However, they are comparable to costs of items at similar facilities, as nothing in the market has changed significantly in recent years.

### III. REQUIREMENTS AND MATCHED OPTICAL SOLUTIONS

Instrument requirements were extracted initially from the ESS Technical Design Report (TDR) [2] and gradually refined with requirements described in the respective instrument proposals. The minimum wavelength band of the instrument suite is shown in figure 1. Here we can see that there are three categories of instrument: those who are interested in wavelengths at and just below 1 Å and above; those interested in 2 Å neutrons and above, and those interested only in cold neutrons of 4 Å wavelength and longer.

Subdividing into long (150 m) and medium (60 m) instruments is informative. The minimum wavelength band of the long instruments is shown in figure 2, where we see that the long instruments are split almost 50:50 into 2 Å and ~1 Å instruments.

For the medium-length instruments, the wavelength bands are shown in figure 3. In that subset, there are two instruments requiring wavelengths around 1 Å, and a third requiring 5 Å.

The shorter instruments follow a similar process, except with the 15 m instruments who are considered to be so short that they are either straight or use a multi-channel bender.

We can now begin to construct a critical performance/cost ratio transport system as a standard, to compare with the baseline systems from the instrument teams. There are four curved guide systems to consider: two sets of curved guides for the 150 metre instruments for the two wavelength ranges; two sets of curved guides for the 60 metre instruments for the two wavelength ranges. Similarly, there are four types of benders for the two lengths and two wavelength ranges. The 150 metre instruments can have a 20 metre long bender within the bunker, and the 60 metre instruments can have a 15 metre long bender, and each of these is designed for different wavelength bands.

#### A. Standard Guide Concept

To compare with the proposed optical systems, a more minimalist neutron guide concept was developed at ESS for these kinds of studies. In this “ESS Standard Guide”, elliptic geometries are replaced with constant cross section geometries or ballistic geometries. Supermirror  $m$  values are capped at  $m = 4$  for 12 m long ballistic focussing sections, and  $m = 1.5$  everywhere else. Note that this concept still provides more than 50% of the neutron flux at 1 Å if the guides are curved, due to the large radii involved with such long guides. The maximum dimensions of the guide are limited to below 4 cm in the curved sections.

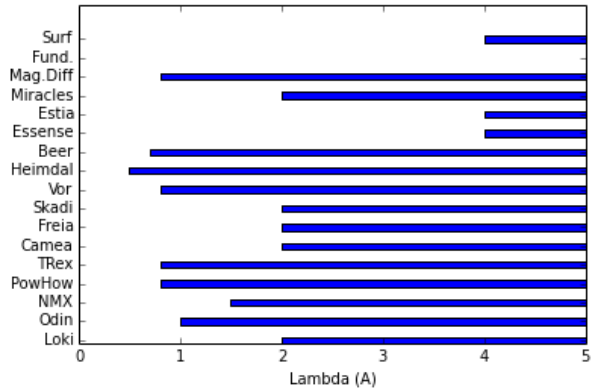


FIG. 1: Wavelengths requested by each instrument on the reference suite at ESS.

#### B. Curved Guides

A number of curved guide options will be considered. The performance estimates follow the work of Mildner [3] which is reliable for the low-divergence parts of the guide systems with low- $m$  values, which is the strategy in this case.

All the guides in the low cost options will be considered to have a maximum size of 200 mm in horizontal and vertical extent. The curved guides have an additional constraint that the curved parts have a width of 4 cm.

The parallel section of the guides is capped at  $m=1.5$ . If we restrict ourselves to guarantee the phase space homogeneity at 1.5 Å then, with 12 m long compression/expansion sections at the ends of the ballistic guides, we only require  $m=4$  coatings. This still provides a maximum beam divergence of  $1^\circ$ . The transmission of this guide system is shown in figure 2. For the 60 metre guides, a higher  $m$  is required to get out of line of sight in a shorter distance. The transmission of this guide system is shown in figure 3.

#### C. Multi-Channel Bender Options

These items are necessary to get out of line of sight quickly in the bunker. The first solution matches the requirements of transmitting 1 Å neutrons, and is described in table I.

The second version of this item is designed to transmit 2 Å neutrons, and is described in table II.

### IV. SUITE COST TOTALS

The cost per instrument as a function of instrument length is shown for the standard instrument options in figure 4 on page 5. There it is clear that a general strategy

TABLE I: 150 metre bender specifications for efficient transmission of 1 Å neutrons.

Parameter	Value
150 m bender width	4.0 cm
150 m bender length	20 m
150 m channel width	0.5 cm
150 m bender m	3.0
150 m nchannels	8.0
150 m bender radius	1250.0 m
150 m transmission at 1 Å	80%
150 m Cost	1.444 M€

TABLE II: 150 metre bender specifications for efficient transmission of 2 Å neutrons.

Parameter	Value
150 m bender width	4.0 cm
150 m bender length	20 m
150 m channel width	2 cm
150 m bender m	2.5
150 m nchannels	2
150 m bender radius	1250.0 m
150 m transmission at 2 Å	88%
150 m Cost	341 k€

TABLE III: 60 m bender for 1 Å neutrons.

Parameter	Value
60 m bender width	3.0 cm
60 m bender length	15 m
60 m channel width	0.5 cm
60 m bender m	3.0
60 m nchannels	6.0
60 m bender radius	937.5 m
60 m transmission at 1 Å	73%
60 m Cost	742 k€

TABLE IV: 60 m bender for 4 Å neutrons.

Parameter	Value
60 m bender width	4.0 cm
60 m bender length	15 m
60 m channel width	2 cm
60 m bender m	1.5
60 m nchannels	2
60 m bender radius	703.0 m
60 m transmission at 4 Å	85%
60 m Cost	193 k€

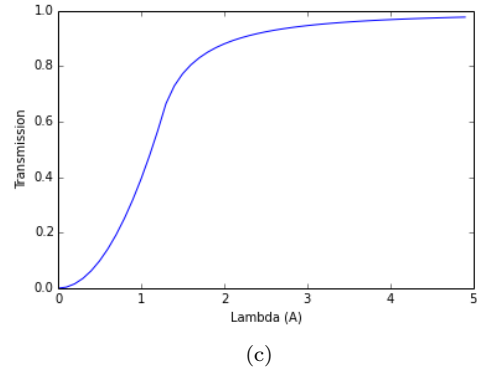
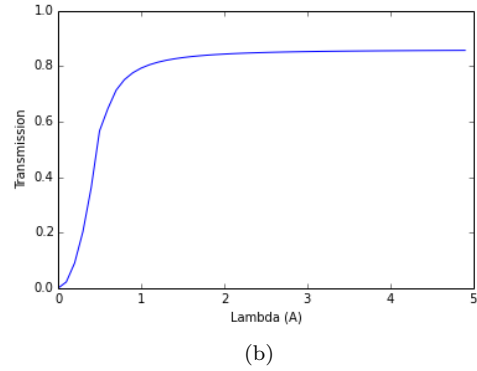
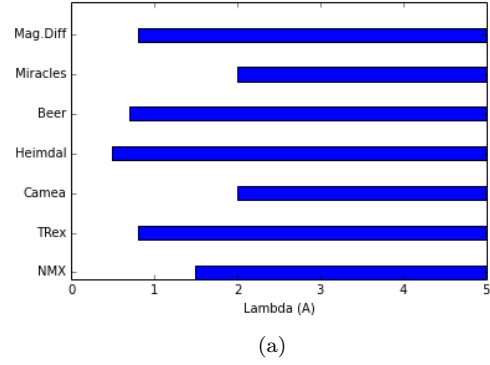


FIG. 2:

(a) Wavelengths requested by the 150 m long instruments at ESS.

(b) Transmission of a multi-channel bender designed to transmit 1 Å neutrons to the 150 m long instruments at ESS. The specifications of this bender are given in table I

(c) Transmission of a multi-channel bender designed to transmit 2 Å neutrons to the 150 m long instruments at ESS. The specifications of this bender are given in table II

of curving all the guides is cheaper overall. The cheapest possible method is using simple curved guides, since the additional cost of multi-channel benders is not offset by the cost savings in shielding outside the bunker. On the other hand, these marginal differences between the curved guides and benders are a small increment to pay

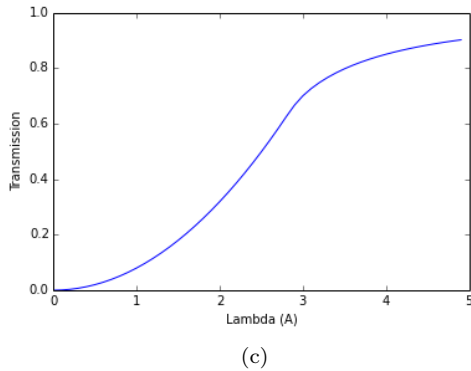
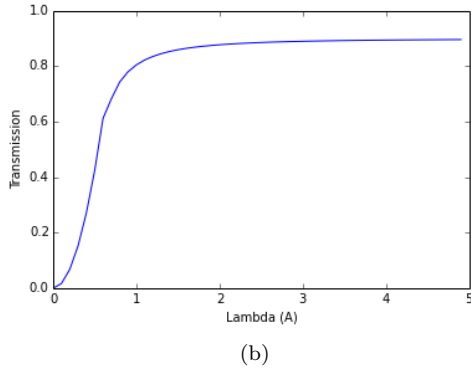
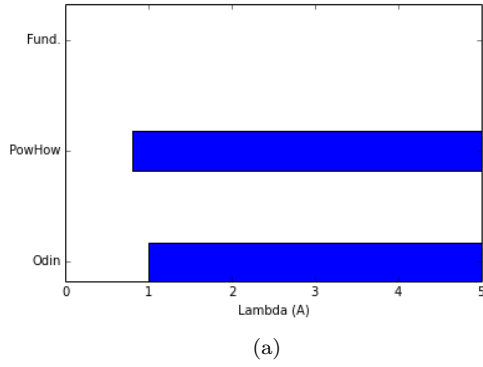


FIG. 3:

(a) Wavelengths requested by the 60 m medium length instruments at ESS. “Fund” corresponding to “Fundamental physics” requests 5 Å.

(b) Transmission of a multi-channel bender designed to transmit 1 Å neutrons to the 60 m long instruments at ESS. The specifications of this bender are given in table III.

(c) Transmission of a multi-channel bender designed to transmit 4 Å neutrons to the 60 m long instruments at ESS. The specifications of this bender are given in table IV.

for likely improvements in the instrument backgrounds.

Furthermore, we also see that the total cost delta for a straight guide *vs* a curved guide is 1-2 M€ per instrument, on average. This seems approximately correct, considering the main cost drivers in the cost delta, namely a  $T0$  chopper, heavy shutter, and enhanced in-

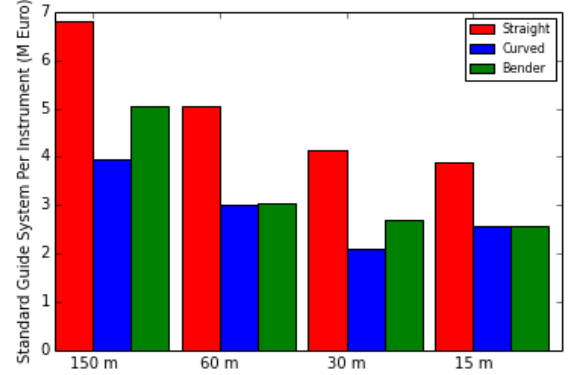


FIG. 4: Cost of each instrument using the standard ESS guide concept, to isolate the cost delta for the different curving options (therefore omitting the baseline suite).

strument cave.

The total instrument suite cost for the full suite is shown in figure 5 on page 5 for each option, and the potential savings in figure 6 on page 6. In these figures,

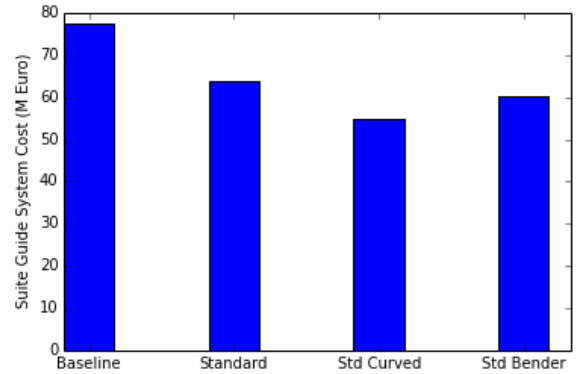


FIG. 5: Total cost for the instrument suite considered.

the following options are costed:

- “Baseline” which is the total of the instrument proposal costs, corrected where necessary (explanation in next paragraph)
- “Standard” which is a reduction of the optical specifications towards a standard ESS guide
- “Std Curved” which forces all beamlines to be curved out of line of sight, losing line of sight 50% of the way down the beamline, in addition to following the ESS standard guide design
- “Std Bender” which follows the ESS standard guide design and has a multi-channel bender to lose line of sight in the bunker.

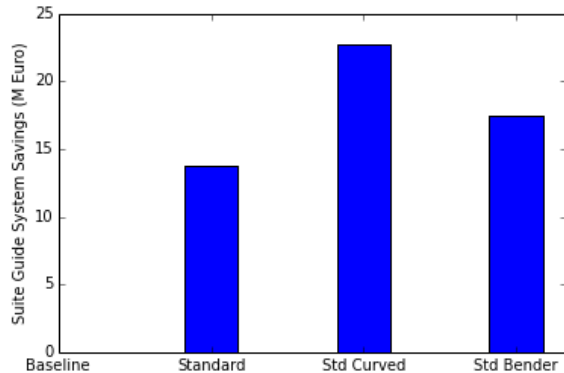


FIG. 6: Total cost saving for the instrument suite considered, for each of the options, relative to the baseline of as-proposed optics geometry.

One can see that, relative to the baseline, the standard curved guide concept is likely to save 24 M€ across the suite, with minimal impact on the instrument performance.

## V. COSTING VALIDATION

For any publicly funded project it is important to get an as good as possible cost indication early and refine estimations as soon as more detailed information becomes available. The instruments described in [2] allowed for an indicative cost, which is part of the total ESS construction cost of 1.843 B€ established in 2013.

Over the last 3 years, the instrument concepts were refined primarily in terms of scientific requirements but not so much in terms of costs. On the other hand it is the central facility's responsibility to manage the available budgets as efficiently as possible to maximise the scope for and involvement of in-kind partners throughout Europe. In order to refine the cost of neutron instrument components (aka beamline components or instrument components or simply components), a workshop was held in early 2014, which involved partners from ISIS in the UK, PSI from Switzerland, and JCNS from Germany, all of which have an extensive and excellent track record of building world-class neutron instruments.

During the workshop, a list of around 20 components with indicative costs — based on recent projects such as ISIS TS-II [4] or the JCNS spin-echo instrument BL-15 at SNS [8] — was established, which included e.g. shutters, benders, instrument caves but also services for installation or staff/labour costs [1]. Although the scope of the instrument programme was not defined at that time, the components were used to

1. Better estimate the costs of the TDR reference suite,

2. To gradually refine costs as instrument concepts became better defined, and
3. To independently assess costs to obtain the best “value-for-money” for all the partner countries involved in the instrument build programme, and consequently the tax payers within the partner countries.

From [1], a cost distribution for instruments as shown in fig. 7 can be obtained. While — for good reason — a

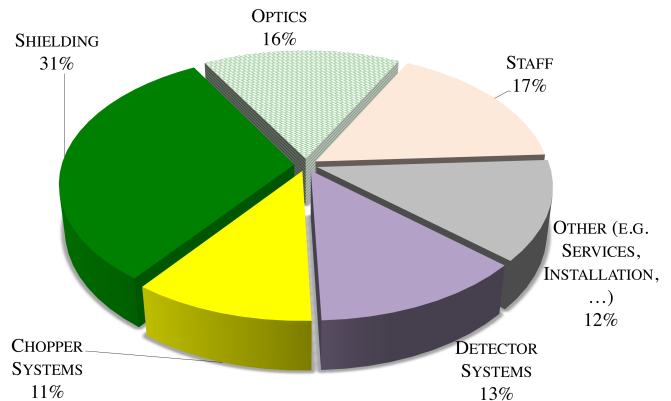


FIG. 7: Approximate cost distribution of components for neutron scattering instruments considered to be built at the ESS.

lot of focus is currently on e.g. detector systems for ESS instruments due to the difficulty to acquire large quantities of  $^3\text{He}$  gas [9], it may come as a surprise that around 47% of the total costs fall into the categories “Shielding” and “Optics”, with 31% and 16%, respectively. For the instruments described in the TDR — with adjustments to consider improvements in the scientific requirements/specifications — one would arrive at an overall cost of around 290 M€. While the reference suite comprises 22 instruments, the current scope of the instrument build programme is 16 (it is worthwhile noting that the 16 instruments are part of the ESS Construction Programme; plans have been developed and will be refined over the next 2-3 years to arrive at 22 public instruments described in [2]).

For a suite of 16 instruments one would estimate costs of 211 M€. As indicated by fig. 7 the majority of the costs are associated with shielding/optical components, and amongst those components the main cost drivers are instrument caves (initially valued at 2.5 M€) and neutron guides (initially valued at 30k€/m; including not only the glass components but also required shielding). A simplistic approach ignoring any cost-benefit analysis would require for only instrument caves and guide systems of 16 instruments a budget of around 83 M€, which is consistent within an error of around 10% with the baseline cost indicated in fig. 6. The arguments provided earlier in terms of optimising e.g. instrument caves as a function of ‘curved/straight’ immediately changes

cost requirements for only instrument caves from around 40 M€ to 26 M€ thus giving a potential cost saving of 14 M€. Similar arguments can be applied for different guide geometries, curvatures resulting in approx. 1 M€ per instrument, and a total of 16 M€ + 14 M€ = 30 M€, which is — again within a 10% error — consistent with results discussed in the context of fig. 6.

In terms of project management one could also use the results indicated in fig. 6 to perform an indicative PERT (e.g. [10]) estimation with

- the *Std Curved option* saving being the optimistic estimation
- the *Standard option* being the pessimistic estimation
- the *Std Bender option* being the best guess estimation

Usually, a PERT analysis is used to regulate optimism and pessimism in schedule estimates, but we can also apply the same logic here for cost option extrema, resulting in a potential saving of 17 M€.

#### A. Approximate Benchmarking

For the moment it is assumed that the cost per instrument can be reduced from 14.5 M€ to 13.5 M€ using the more conservative PERT estimation. At ESS the average length of an instrument is 90 m due to the long pulse design. At short pulse spallation sources such as SNS or ISIS instruments are on average around 50 m long, resulting in an average cost of around 12.2 M€<sub>2015</sub>.

ISIS' recent TS2 project was established with an budget of 145 M£, out of which 100.5 M£ were allocated to the core project and 27 M£ for the instrument project with the remaining 17.5 M£ for instruments coming from the EU and collaborating European countries [5], a similar model that is used for the phase 2 upgrade of TS2 [4]. The initial scope of TS2 included 7 instruments or an average cost of 6.4 M£. A conservative estimation of inflation would assume a cost increase of around 20% since 2005 [6] resulting in 7.7 M£<sub>2015</sub>. Over the last years the average exchange ration between € and £ was 1:1.28 [7] giving 9.8 M€<sub>2015</sub> for an average instrument of around 50 m length. The main difference between the 12.2 M€<sub>2015</sub> and the 9.8 M€<sub>2015</sub> can easily be explained by a slightly higher-level of complexity of ESS instruments due to the different source characteristics, but also due to the fact that ESS is a green field site. Also, it can be assumed that additional effort, in particular with regard to installation, is required to due to the in-kind nature of the project.

While all the numbers are only indicative — details matter after all — they nevertheless show that proper strategies and analyses such as benchmarking, component breakdown, cost-benefit analysis or efficient standardised technical solutions via optimised non-recurrent

engineering designs have the potential to optimise costs, which is not a surprise in itself. Although the focus here is on optical and shielding components any cost optimisation has two major consequences: obviously, it reduces overall costs, which is in the interest of the project governance and the funding agencies; but secondly, because standardised systems are proposed with almost no or minimal impact on performance, costs related to installation, maintenance and spare parts are being reduced, which in turn will lower the operational costs. As the operational costs are estimated to be typically 4 times the initial investment cost in case of a scientific facility, this has a significant effect over the lifetime of the facility.

It may actually be more appropriate to refer to a cost optimisation of  $x$  M€ because the aim is not to minimise the costs by all means but to rather use the available budget more intelligently and focused by e.g. redistributing costs into areas such as computing, installation or contingency if required, but also to compensate for any shortfalls of the initial assumptions when creating the list of components. It is also worthwhile noting that at this point no significant de-scoping of instruments in terms of their scientific performance or functionality is discussed. This is an alternative project management tool that, whilst popular and utilised in large scale scientific projects, nonetheless can have a devastating impact on the scientific output of a facility, and the methodology presented here should probably be used *before* removing scope from the instrument projects themselves.

## VI. CONCLUSIONS

We have used neutron optics geometry combined with a cost-benefit analysis balancing shielding costs, to propose an optimisation of the ESS instrument suite budget. Cost savings in the order of 20 M€ are identified compared to the baseline budget as defined in the adjusted instrument proposal costs. This cost saving has been compared with instrument costs at existing facilities, and found to be within reasonable agreement. While this approach is common in industry, it is perhaps less widely used in scientific projects, and the management challenge to unlock these savings, at any facility, is to establish a strong central coordination mechanism: to supply standard concepts and systems such as the ones described here; to provide a core team to manage the suite optimisation; and to intervene when deviations from the standards are being pursued, particularly in the cases where small performance increases are accompanied by large cost impacts.

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